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TRANSIT TIME LIDAR MEASUREMENT OF NEAR-SURFACE WINDS IN THE ATM--ETC(U)
MAY 79 T L BARBER, R RODRIGUEZ

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MAY 1979

By

T.L. BARBER
R. RODRIGUEZ

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US Army Electronics Research and Development Command
Atmospheric Sciences Laboratory
White Sands Missile Range, NM 88002

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This report deals with an improved model of a transit time laser radar. The technique measures a backscatter signal from atmospheric aerosols from two sample volumes a known distance apart in the atmosphere. These two signals are cross-correlated to obtain the time of flight of aerosol inhomogeneities as they move from one volume to another. Once the time of flight is calculated, the windspeed can be obtained since the distance between sample volumes is known. This model utilizes a copper vapor laser as the transmitter source. (Cont'd)

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Crosswind data were successfully obtained in the unperturbed atmosphere under very clear, and thus difficult, conditions with horizontal visibility of 130 km. Results of the experiments showed that even under these conditions the variablilty of the aerosol concentration was high enough to permit a correlation that generated a reliable wind measurement at least once a minute. Transit time lidar wind measurements agreed within 15 percent of values simultaneously recorded with an anemometer.

PREFACE

The authors thank Mr. Noah Montoya of the Meteorological Support Division for his skillful assistance in calibrating and manning the range gate system during the data collection phase of the experiment. The authors also thank Dr. H. Auvermann from the Physical Science Laboratory at New Mexico State University for the skillful computer programming and mathematical techniques he used in reducing the complex lidar data.

CONTENTS

INTRODUCTION

The atmospheric wind field affects the United States Army Tactical operations. For example, the impact point of a ballistic projectile is affected by crosswinds prevailing along its trajectory. If the gunner has knowledge of the wind structure before aiming the gun, he can make the necessary corrections to achieve improved and more accurate firepower. This will, in turn, increase the first-round-hit probability and standoff range of our friendly forces. Optical remote wind sensors have displayed the potential capability of providing the wind structure information along the forward trajectory of ballistic projectiles. This report discusses the experimental setup of a prototype transit time lidar system (TTL), an optical remote wind sensor, and presents some preliminary data collected with the system. TTL is an exploratory development prototype of an active remote crosswind sensor that is capable of measuring crosswind speed (component perpendicular to the laser beam) at predetermined small volumes in the atmosphere.

The TTL method of measuring wind velocity depends on the fact that atmospheric dust is not uniformly mixed in the atmosphere. As these inhomogeneities or particulate patterns are carried by the wind, they change as a function of time. However, during the sample period of the TTL, the change is so small it is assumed to be nil. The TTL transmits a pulsed laser beam which illuminates two predetermined volumes in the atmosphere. The distance between these two sample volumes is determined by the geometry of the receiving telescope (optical receiver) shown in figure 1. A set of photomultipliers converts the backscattered light energy into two electrical signals. To determine range, the electrical signals are gated by the ranging circuit in the electronic receiver. These two gated signals are then digitized and cross-correlated to extract the transit time, which is the time needed by the pattern to travel from one volume to the other. With this transit time and distance between sample volumes, the perpendicular wind component (magnitude and direction) can be calculated.

BACKGROUND

In the past, three methods to measure winds remotely with lidar have received considerable attention. These three methods are based on the phenomenon that aerosols in the atmosphere move with the same velocity as the wind. Schwiesow[1] has used the doppler principle with a CO_2 lidar

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[1]R. L. Schwiesow, R. E. Cupp, M. J. Post, and R. F. Calfee, 1977, "Coherent Differential Doppler Measurements of Transverse Velocity at a Remote Point," Applied Optics, Vol 16, No. 5, pp 1145-1150

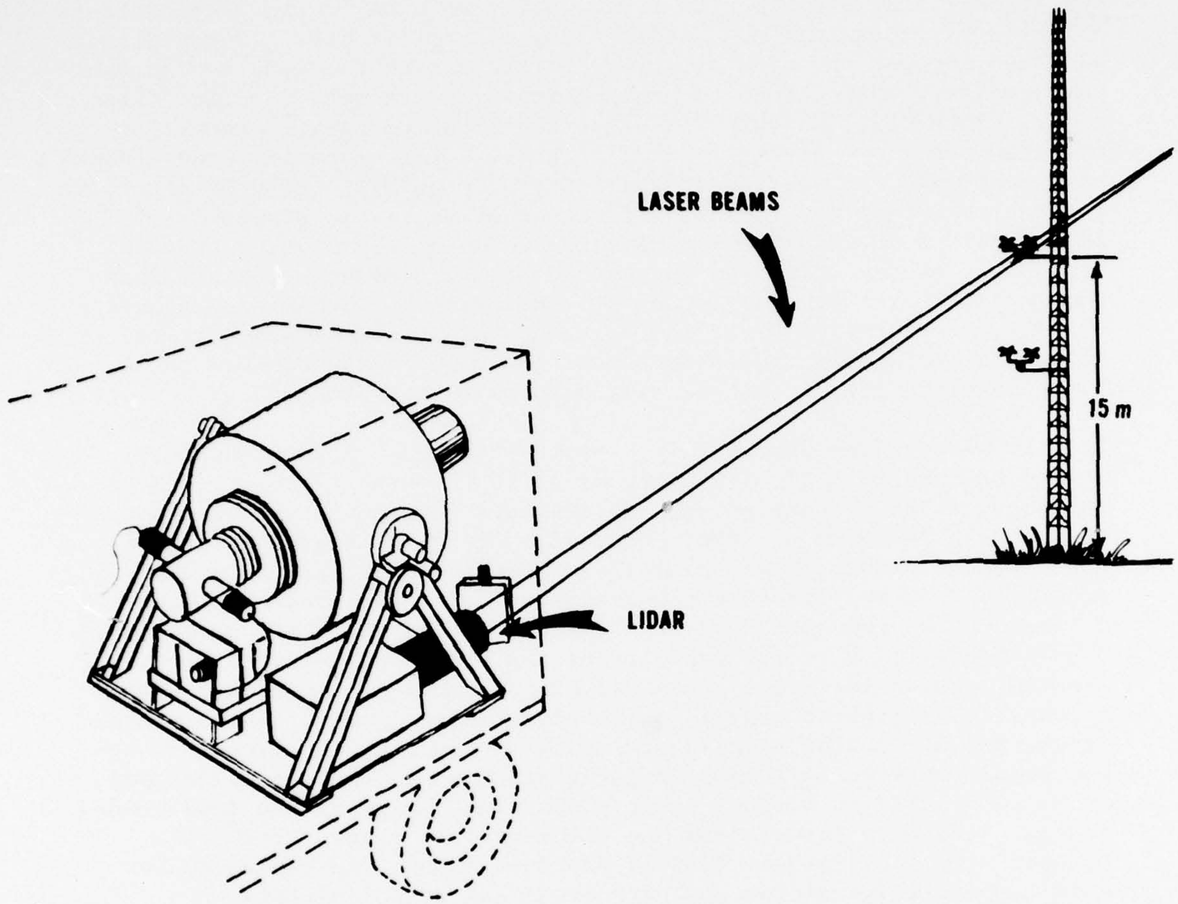

Figure 1. A sketch of the lidar field setup at LC 36, White Sands Missile Range, NM. The transmitter is a copper vapor laser, and the receiver is a cassegrainian telescope. The reference anemometer is attached to the meteorological tower.

system to measure the radial component of the wind velocity. Leuthner[2] has measured the motion of large dust conglomerates (approximately 1,000 m wide) to determine wind velocity in two dimensions at ranges up to 10 km. This second method requires at least 2.5 min to obtain sufficient data to compute wind velocity. The third method is known as the transit time lidar (TTL) approach. Derr[3] has done some preliminary work in this area; however, Barber and Mason[4] have conducted most of the advanced work in this area, including development of a prototype model.

The TTL effort at this laboratory began in 1972 when a nitrogen laser was utilized as the transmitter and an electronic range gate was used in the receiver.[4,5] This approach proved that the TTL method of remotely measuring windspeed was feasible. However, there were two obvious drawbacks: (1) the pulse repetition frequency (prf) of the nitrogen laser was very slow, forcing the sample volumes to be too far apart to obtain meaningful correlations; (2) the beam divergence of the nitrogen laser was approximately 6 mrad, which did not permit efficient use of laser energy at ranges of interest.

To alleviate these problems, the nitrogen laser was replaced with an argon ion laser in 1974. During this phase of the experiment, energy per pulse was determined to be insufficient; furthermore, the laser was extremely sensitive to vibration and therefore could not be employed in field experiments.[6] Thus, in 1977 a copper vapor laser was substituted as the TTL transmitter. The copper vapor laser with a beam

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[2]T. G. Leuthner and E. W. Eloranta, "Remote Measurements of Longitudinal and Crosspath Wind Velocities with a Monostatic Lidar," paper presented at the 8th International Laser Radar Conference at Drexel University, Philadelphia, PA, June 1977

[3]V. F. Derr, G. M. Lerfald, and M. J. Post, 1978, "Measures of Inhomogeneity of Aerosols," ERADCOM Report ASL-CR-78-8017-1. Atmospheric Sciences Laboratory, White Sands Missile Range, NM

[4]T. L. Barber and J. B. Mason, 1974, "A Transit-Time Lidar Wind Measurement: A Feasibility Study," ECOM Report 5550. Atmospheric Sciences Laboratory, White Sands Missile Range, NM

[5]R. L. Armstrong, J. B. Mason, and T. L. Barber, 1976, "Detection of Atmospheric Aerosol Flow Using a Transit-Time Lidar Velocimeter," Applied Optics, Vol 15, No. 11, pp 2891-2995

[6]T. L. Barber and R. B. Loveland, "The Transit-Time Laser Radar as a Remote Wind Measuring Device," paper presented at the 7th International Laser Radar Conference at SRI Menlo Park, CA, November 1975

divergence of less than 0.5 mrad concentrated more energy per pulse in a given volume of atmosphere, had much better stability, and had a sufficiently high prf.

The laser energy from the copper vapor laser is approximately 1 mJ per pulse, which is the same amount of energy available from the nitrogen laser. However, because of its large beam divergence, only about 0.1 percent of the radiation from the nitrogen laser illuminated the sample volumes. The copper vapor laser has a beam collimator which concentrates all the available energy in a 2-cm circle at 70 m. (The beam collimator and the method of producing the two beams are illustrated in figure 2.) In addition, ultraviolet light is scattered more efficiently than visible light by atmospheric particulates.[7] These two factors increase the scatter return per pulse by a factor of 37. Furthermore, the pulse repetition rate increased 100 times (from 60 to 6,000), thereby increasing the potential information rate by a factor of 3,700. The copper vapor laser was more adaptable to field operations because it is not very susceptible to mechanical vibrations or thermal changes, and also because it is relatively easily and quickly aligned.

METHODOLOGY

The method of measuring winds by illuminating two sample volumes with a single laser is shown in figure 2. As the laser beam comes out of the collimator, it strikes a director front surface mirror. After being reflected, the beam goes to the two staggered pointing mirrors. Each of these mirrors intercepts half of the circular beam and reflects it to the sample volume. The illumination of each sample volume is maximized by adjusting each pointing mirror independently. The transmitted energy that is backscattered by the atmospheric particles is collected by the optical receiver, a telescope focused at 70 m.

The copper vapor laser outputs two wavelengths simultaneously: 5106 and 5782 angstroms. About three-fourths of the total energy is produced at the 5106-angstrom wavelength.

Figure 3 shows a diagram of the alignment procedure that was used. As the laser is turned on, the copper starts to heat up and a fluorescent output is visible on a sheet of paper placed in front of the laser. The first dim output produced is blue with a slow transition to pink, then to green. If the optics have not been aligned previously, the output might look like figure 3A. The first step is to adjust the rear mirror micrometer until an output like that shown in figure 3B is

[7]H. C. Van de Hulst, 1957, <u>Light Scattering by Small Particles</u>, John Wiley and Sons, Inc., New York

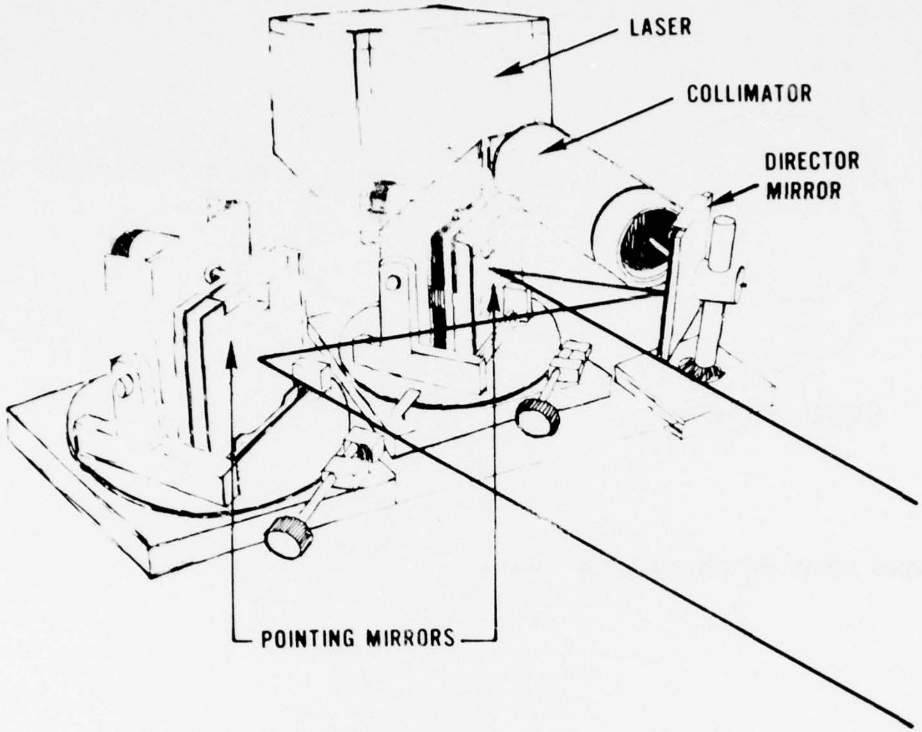

Figure 2. Method of forming two beams from a single laser. The main beam is expanded by the collimator and then redirected by the director mirror. The pointing mirrors are staggered in such a manner that each intercepts and reflects half of the beam. These mirrors can be adjusted individually to obtain efficient illumination of the sample volumes.

LASER ALIGNMENT

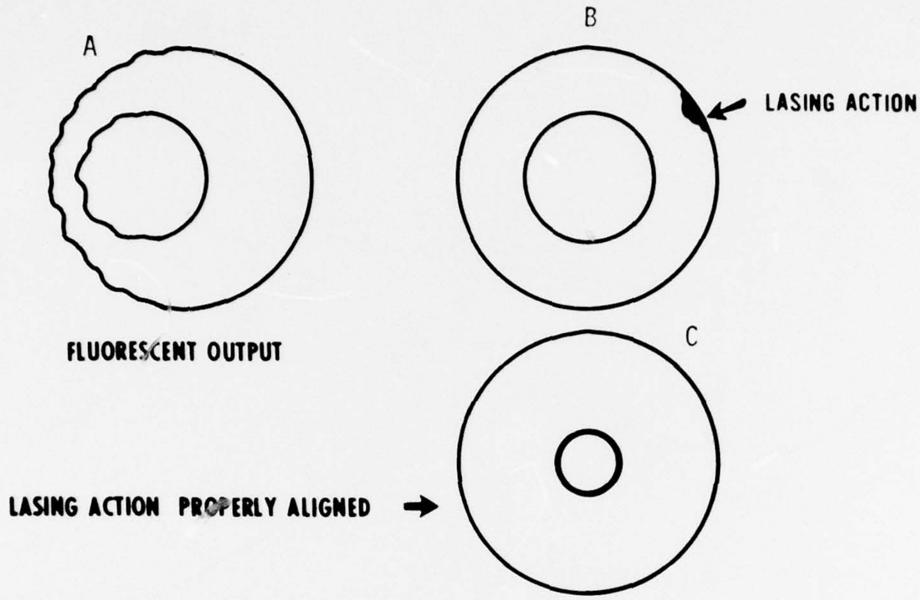

Figure 3. Laser alignment procedure. "A" shows the condition when the laser is out of alignment. The image produced by the laser on a white piece of paper is a dim green image with the inner portion only slightly brighter than the outer portion. Adjusting the rear reflector produces condition "B" where the image is still dim green, but the inner portion is centered. At this point, lasing action will be visible as shown by the arrow. Next, a no. 14 welder goggle plate is placed in the beam, and the front reflector is adjusted to achieve the condition at "C" where the inner section is relatively brilliant green and the edge is evenly illuminated.

obtained. At this point a welder's goggle number 14 is placed at the laser output port to reduce the intensity. The second step is to adjust the front mirror micrometer to go from 3B to the shape shown in 3C. When the optics are properly aligned, the laser spot becomes circular and its edge is brilliant and even.

The scattered light from the sample volumes collected by the telescope is converted to an electrical signal by a pair of photomultipliers. Both of these wavelengths are transmitted into the atmosphere, but a 20-angstrom optical filter in front of the photomultiplier tubes, centered at 5106 angstroms, reduces the extraneous light noise and passes the major frequency of the laser. The signal from each of the two photomultipliers is fed to a gate circuit. A time sequence of this gate circuit operation is presented in figure 4. The signal that is obtained through the gate circuit from one photomultiplier is an average return from an atmospheric volume of 4 m in length and 2 cm in diameter at a range of 70 m. The other photomultiplier gated signal is from a similar volume horizontally displaced 24 cm.

The data from each gate are recorded on an analog tape recorder together with the three analog signals from a UVW/anemometer. One of the anemometer's sensors is lined up perpendicular to the laser beam as shown in figure 1. A synchronizing pulse (data flag) is also recorded. The data from these tapes are digitized by using the synchronizing pulse as reference, waiting 50 microseconds, and reading a voltage value from photomultiplier 1, photomultiplier 2, and the perpendicular wind component.

Figure 5 is a sample of the backscatter return. The exact source of the high frequency variations in the backscattered signal is unknown. However, results from previous experimentation and theoretical considerations have shown that the data of interest will fall in the frequency range of 0.1 to 30 Hz. This is corroborated by considering an average windspeed of 10 m/sec and dust irregularities from 0.5 m to 10 m diameter. In the case of the dust irregularity having a size of 0.5 m and moving at 10 m/sec, it will take 0.05 sec for the irregularity to go through the beam, which is equivalent to a frequency of 20 Hz. In the case of a 10-m diameter dust irregularity going through the beam, when the wind blows at 10 m/sec, the transit time will be 1 sec, which is equivalent to a frequency of 1 Hz.

The total information recorded on analog tape is dependent on the laser pulse repetition rate which is a key characteristic in determining the maximum wind velocities which can be ascertained. Information theory states that at least three pulses are needed per atmospheric volume illuminated as a particulate pattern travels through the two probed volumes. As mentioned before, in the case of the nitrogen laser, TTL operation was limited because its maximum prf was only 100 Hz. To minimize these problems and to insure collection of proper data as

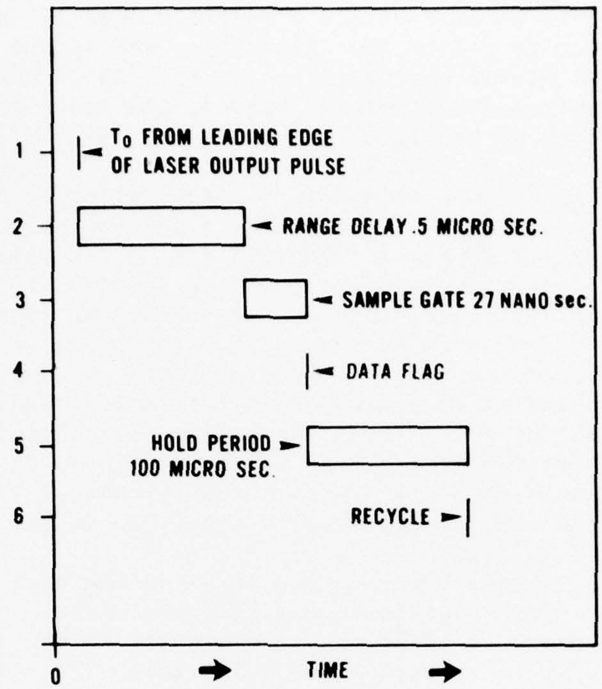

Figure 4. Time sequence of gate circuit operation (one cycle).

1 - electronic pulse produced by a photodiode looking at the surface reflection from one of the laser cavity windows. This is the sync pulse that starts gate operation.

2 - range delay from transmitter to sample volume.

3 - sample volume length determination.

4 - data flag to initiate sampling by the A/D converter.

5 - period during which signal is held until A/D converter finishes sampling.

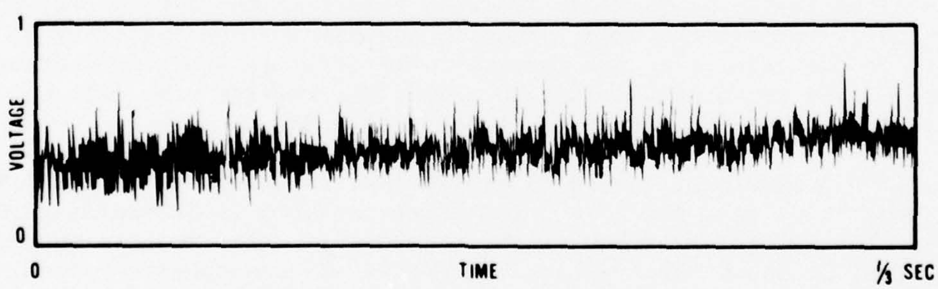

Figure 5. Plot of gated backscattered voltage signal vs time. Note the high frequency content in the signal.

required by information theory, the distance between samples was chosen as 1.2 m. With these constraints, the maximum windspeed that could be measured was 16.6 m/sec. For low winds, such as 1 m/sec, the transit time was 1.2 sec. During this time period, the atmospheric particulate pattern changed appreciably; therefore, there was less correlation between signals. As the correlation decreased, the probability of obtaining a reliable wind measurement decreased too.

The problem was resolved by replacing the nitrogen laser with a copper vapor laser which is capable of generating prf from 800 to 10,000 Hz. It was decided to use a prf of 6,000 Hz, and 24 cm as the distance between samples. With this improved configuration, a low wind velocity, such as 1 m/sec, produces a transit time of 0.24 sec. If the operating prf is 6,000 Hz, then 1,440 pulses occur during the transit time. Furthermore, the transit time is so short that deterioration of the atmospheric particulate patterns is negligible. When high winds, such as 50 m/sec are present, the transit time becomes 1/208 sec; in this time interval, the copper vapor laser generates 29 pulses, which is quite adequate for the computational algorithm.

DATA ANALYSIS AND RESULTS

As illustrated in the last paragraph of the preceding section, the frequency ranges which contain the desired wind information are inversely proportional to the size of the existent turbulent atmospheric cells. Knowing that at the 15-m altitude probed the dust irregularities, which backscatter the lidar signal, are carried in turbulent cells of a size range 5 to 20 m and that the wind velocities of interest fall in the vicinity of 10 m/sec, the TTL data should lie in the frequency range below 30 Hz. However, the raw data collected contained many high frequency components, as shown in the sample plot of figure 5. These high frequency variations in the data had the effect of producing "unclear" correlations, which in turn generated unrealistically high wind velocity values. Figures 6A through 6F show examples of such correlations; the most striking examples are the correlograms of figures 6B and 6C which yielded the extremely high velocity values of 240 and 180 m/sec, respectively. Sources of the high frequency components include "pulse-to-pulse" variations in the laser output, microstructures in the particulate concentration, and optical turbulence in the atmosphere.

To eliminate the high frequency components from the raw data and thus decrease the error in the results, a computer filtering subroutine was employed. The algorithm used by this subroutine consists of Fourier-transforming the raw data, removing all undesirable frequencies, and then inverse Fourier-transforming the resultant data. Since the data are removed or filtered by a computer, the high cutoff frequency and the type of filter roll-off curve can readily be changed.

The data shown in this series of figures were Fourier-transformed and passed through a filter with a cosine squared high frequency roll-off and a 3 dB point at 45 Hz. Figures 6A through 6F were produced with consecutive data blocks, covering a total time period of 4.2 sec. The point in time at which these data were taken is shown in figures 8 and 9 by an arrow.

These six correlations are presented to illustrate problems produced by the high frequency components (4 to 45 Hz) in the data. These high frequencies can be related to the shape effect of the dust cells and optical turbulence in the atmosphere along the laser beam.

The average wind velocity measured by the reference anemometer during this time period was 4.75 m/sec.

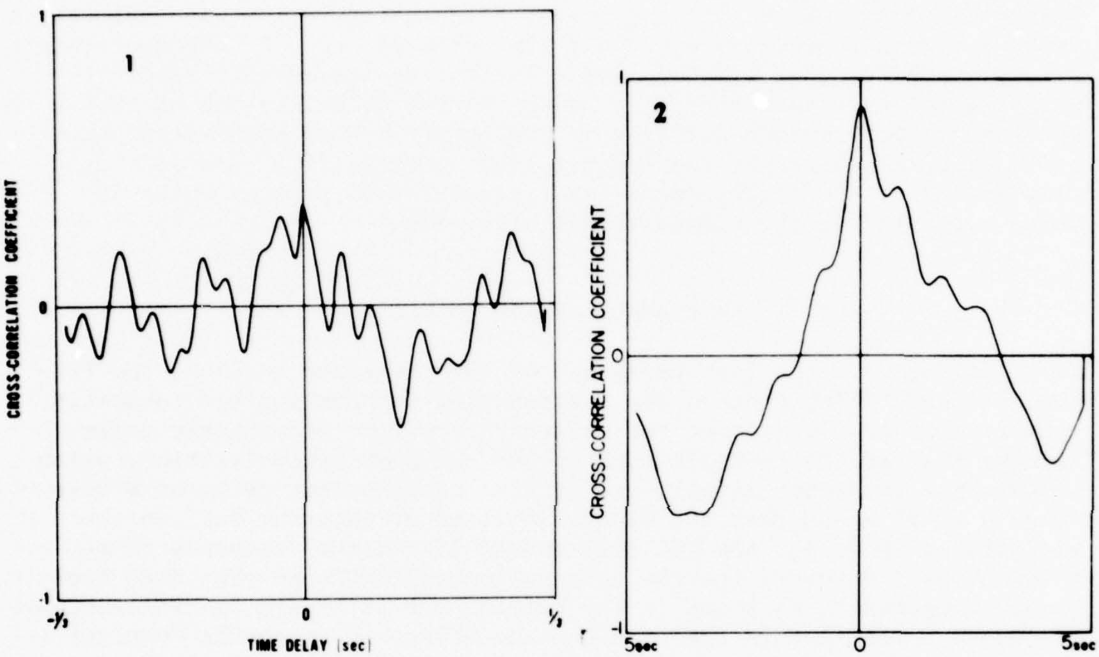

Figure 6A. Cross-correlation with a poorly defined maxima. Three peaks with a similar maximum amplitude are present. Calculated wind velocity 22.3 m/sec.

Figure 6B. A well-defined cross-correlation but unrealistically high calculated wind velocity of 180 m/sec. Time delay between graph ordinate and correlation maximum is 0.0013 sec.

Figure 6. Cross-correlation of two data blocks, each with 4096 data points taken at a rate of 6000 Hz.

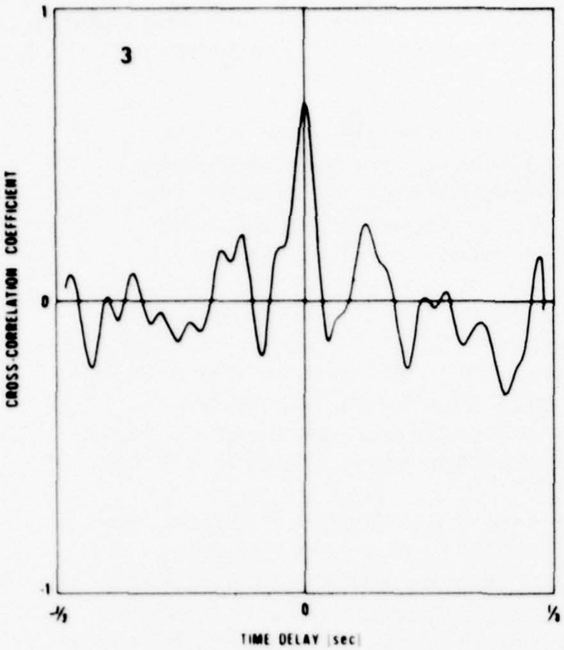

Figure 6C. A well-defined cross-correlation maximum, but unrealistically high calculated wind velocity: 240 m/sec.

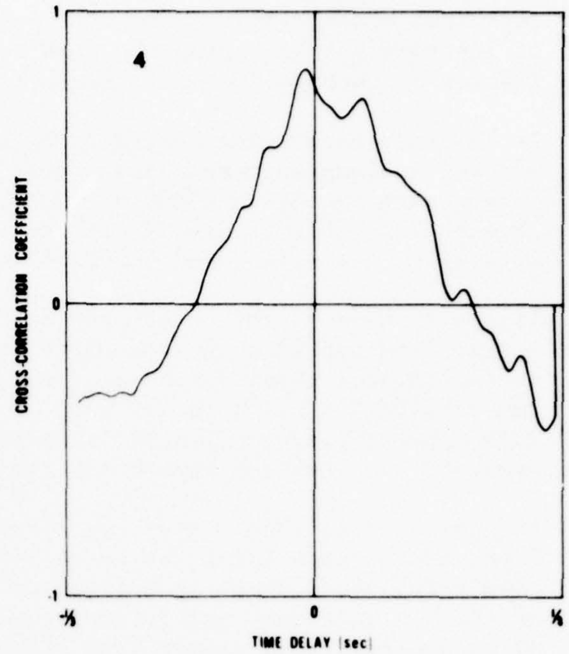

Figure 6D. Cross-correlation with a single, but somewhat broad, maximum. Calculated wind velocity: 31.3 m/sec.

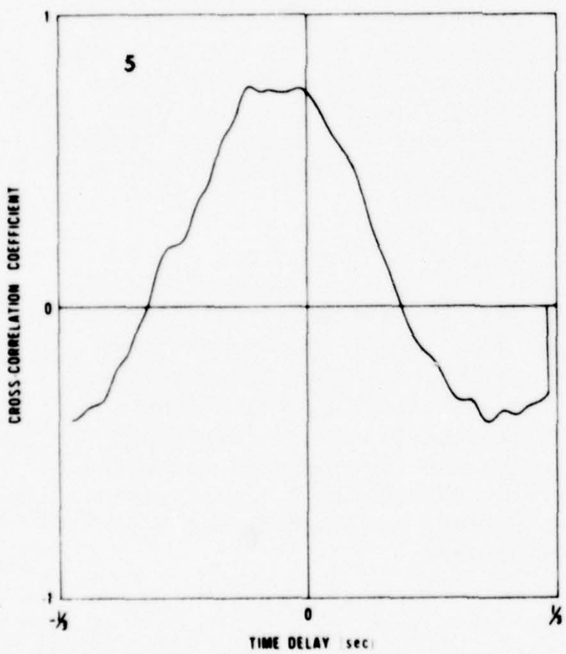

Figure 6E. Cross-correlation with a poorly defined broad correlation maximum. Calculated wind velocity: 9.1 m/sec.

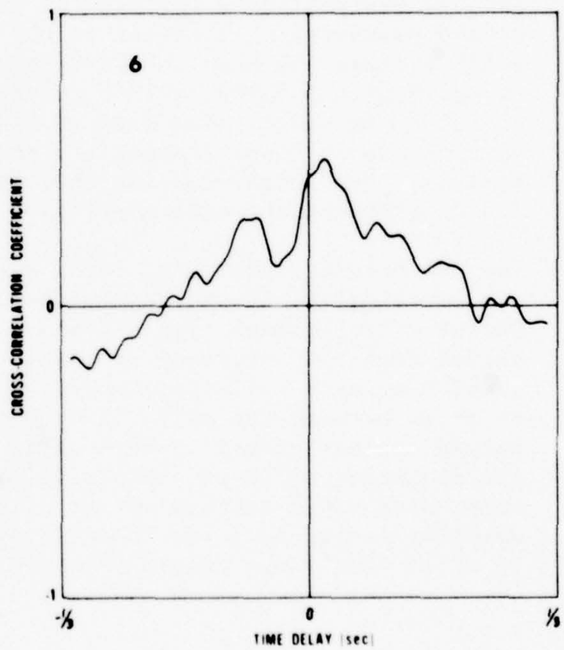

Figure 6F. Cross-correlation with a broad and poorly defined maximum. Calculated wind velocity: 3.3 m/sec.

Figure 6. (cont)

Empirical evaluations of the filtered data were conducted, and the results of incrementally changing the high cutoff frequency are presented in figures 7A through 7C and in table 1.

As the most meaningful correlations occurred when the size of the aerosol inhomogeneities ranged from 1 to 8 m, it became important to investigate how often these aerosol inhomogeneities show up in the atmosphere. This frequency of occurrence is important because it determines how often wind velocity measurements can be obtained.

Figure 8 shows a plot of the sum of the first ten low frequency harmonics, and experiments determined that when this sum exceeded 0.25 of the highest total value, a cross-correlation which provided meaningful results for the data collected in this experiment was obtained. This type of pattern of dust inhomogeneity was found to occur at least every 60 sec when the horizontal visibility was approximately 130 km.

Two parameters, sample time and filter band-pass characteristics, were found to be quite important in obtaining meaningful correlations. A meaningful correlation is defined as one that generates a comparison of the TTL wind data and reference anemometer data within 15 percent of each other. The sample time affected the shape of the correlogram's maximum, which in turn produced "unclear" correlations. Sample times of 0.67, 2.0, 4.67, and 10.0 sec were evaluated, and the conclusion was that the 4.67 sec sample time produced correlograms with a single, well-defined maximum and a correlation coefficient of 0.85 or greater. The second parameter of interest is the filter band-pass characteristics, which include the high cutoff frequency, low cutoff frequency, and type of roll-off. A filter with a cosine squared roll-off curve was used, and the 3 dB cutoff frequency was set at 3.0, 2.0, and 1.0 Hz. The results due to these changes are shown in figures 7A through 7C. After analysis, the conclusion was that setting the high frequency cutoff at 2.0 Hz produced the most meaningful correlograms.

The low cutoff frequencies tried were 0.2, 0.4, 0.5, 0.6, and 0.7 Hz; and empirically, it was determined that 0.6 Hz produced the most meaningful correlograms. Table 2 shows a comparison between wind velocity values from the reference anemometer and TTL. These values were computed from data collected over a 5-min period. Although fair agreement is shown between the pairs of values, the conclusion is that these values are not closer to each other because the lidar and anemometer are measuring different sample volumes, and also because the reference anemometer has a certain amount of inertia. Nonetheless, during this sampling period only one lidar wind measurement was outside the 5 to 13 m/sec wind range recorded by the anemometers.

For this series of figures, the large sample time is accomplished by obtaining a new data block of 4096 data points where each new data point is the summation of 15 old data points. The new data block was Fourier-transformed, filtered, and inverse Fourier-transformed before the cross-correlation was computed. This group of three correlograms shows the effect of varying the high cutoff frequency. Table 1 shows these same results in numerical form.

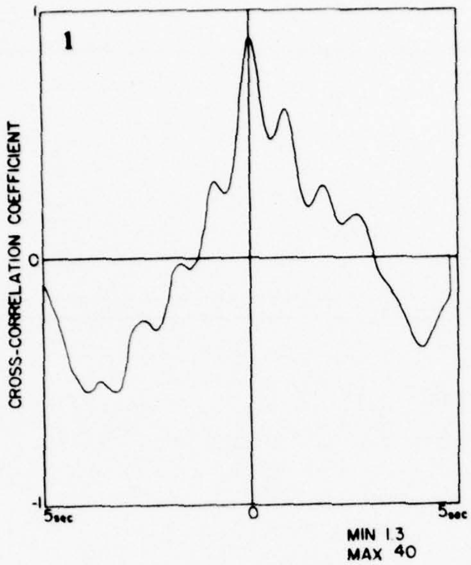

Figure 7A. A cross-correlation with a well-defined maximum. High frequency filter cutoff: 3 Hz. Calculated wind velocity: 8 m/sec. Measured wind velocity: 4.75 m/sec, 68% high.

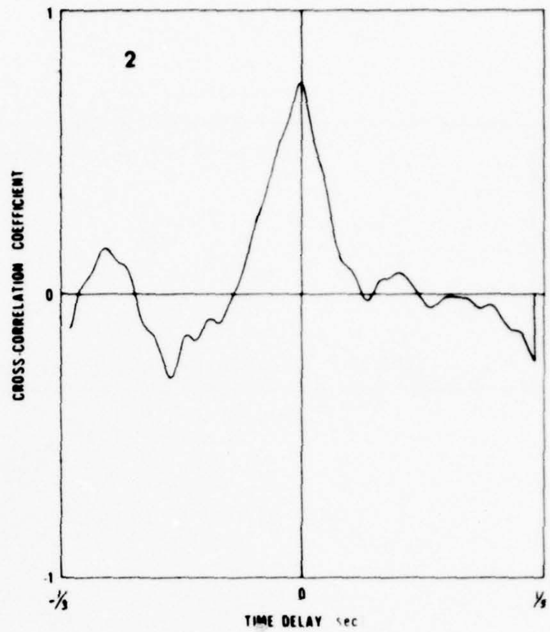

Figure 7B. A cross-correlation with a well-defined maximum. High frequency cutoff: 2 Hz. Calculated wind velocity: 5.3 m/sec. Measured wind velocity: 4.75 m/sec, 12% high. A reasonable comparison.

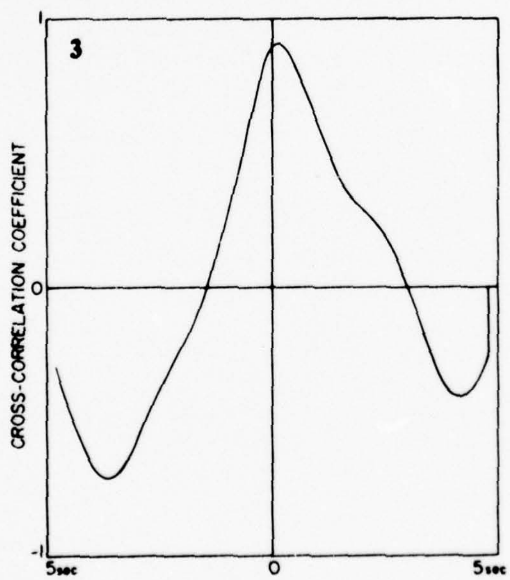

Figure 7C. A cross-correlation with a well-defined yet slightly broadened maximum. High frequency filter cutoff: 1 Hz. Calculated wind velocity: 1.2 m/sec. Measured wind velocity: 4.75 m/sec, 75% low. The frequencies from 1 to 2 Hz should not have been removed.

Figure 7. Cross-correlation of two 10-sec data blocks.

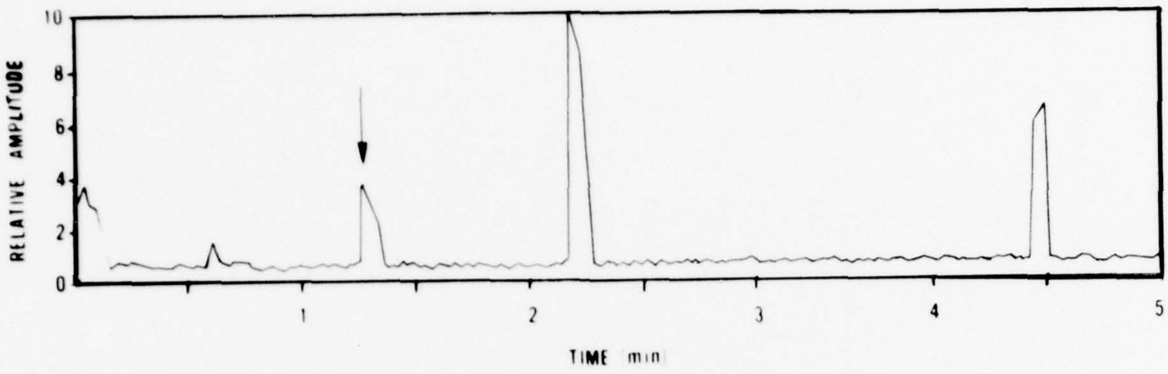

Figure 8. Time plot of the first 10 low frequency harmonics in the Fourier-transform of 4096 point data blocks. These frequencies extend from 1.5 to 15 Hz. *It was empirically* determined that when the curve exceeded 1.5, a meaningful correlation was obtained.

TABLE 1

SETTING OF FILTER HIGH

CUTOFF FREQUENCY

Figure	Frequency (Hz)	Calculated Crosswind Velocity (m/sec)
7A	2.9	8.0
7B	2.0	5.3
7C	1.0	1.2

The measured averaged wind velocity, during the period when the above data were collected, was 4.75 m/sec.

TABLE 2

CROSSWIND MEASUREMENT COMPARISON

Reference Anemometer (m/sec)	TTL Measurement (m/sec)
9.6	14.7
10.0	10.3
6.8	4.7
10.8	6.0
10.4	6.0

Each of these data samples was 4.67 sec long. Low cutoff frequency was 0.6 Hz and high cutoff frequency was set at 4.0 Hz. Cross-correlations were well-defined.

CONCLUSIONS AND RECOMMENDATIONS

The copper vapor laser performed well as the transmitter for the TTL. Its operational characteristics make it suitable for experimental field use because it is relatively easy to align and is not very sensitive to vibration.

With the present configuration of TTL, reasonable crosswind measurements were obtained from the unperturbed atmosphere when the visibility was approximately 130 km. The best results were obtained when a band-pass filter with a high cutoff frequency of 4 Hz and a low cutoff frequency of 0.6 Hz was used to filter the raw data from both photomultipliers. Using a sample time of 5 sec, TTL is capable of measuring crosswind at least once every 60 sec at a height of 15 m. As the horizontal visibility decreases, crosswind data can be obtained much more easily because the amount of backscatter signal increases.

The degree of agreement between TTL and the reference anemometer values can be improved by optimization of the system's parameters, such as sample volume dimensions, laser prf, and distance between sample volumes. Furthermore, this optimization will also increase the range of operation to the point where a range of 4 km in the unperturbed atmosphere seems reasonable.

The first step in a follow-up program should be analysis of all the available data. After that, data under different meteorological conditions should be obtained and reduced. A collective analysis of all the data should be sufficient to evaluate the TTL's performance. Future efforts should also include an investigation of the optimization of the mathematical algorithm. As part of this investigation, the sample time and band-pass filter characteristics should be studied.

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